REPORT OF THE ANGLO-US MEETING ON COOPERATION FOR CLEANER SEAS: BRIGHTON, UNITED KINGDOM 6-7 MARCH 1994

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Abstract

A joint US/UK workshop met in Brighton, England on March 6 and 7, 1994. The four working groups at the meeting identified specific research areas where significant payoffs are possible from a modest trans-Atlantic collaboration. The workshop, sponsored by the Ocean Engineering Program of the NSF (US) and the Marine Technology Directorate (UK), was entitled "Cooperation for Cleaner Seas." Specific recommendations include: environmental modeling, new *in-situ* sensors (such as concentrations of metals, nutrients, and organics, shear and turbulence in the water column, and non-invasive studies of benthic community structure), and autonomous instrument platforms for pollution monitoring and pipeline inspection.

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OVERVIEW

In recent years, there has been increasing interest in understanding the impact of human activities on the environment. It has been recognized that such impact can occur over a wide range of spatial and temporal scales, both local (pollution) and global (climate change). This joint workshop was convened to consider how new technologies can be applied to understanding the marine environment on both local and global scales.

On a global scale, interest in climate change has lead to the development of a wide range of computer models of the global environment. Currently the sophistication of the models exceeds the quality and quantity of the input data, particularly with respect to the oceans. There are major programs attempting to address this issue (e.g. World Ocean Circulation Experiment, Joint Global Ocean Flux Study, etc.). These programs are limited, however, by the high cost of gathering data from the oceans. Autonomous underwater vehicles (AUVs) offer a new tool for acquiring spatially distributed measurements at low cost, dramatically changing the economics of data collection in marine environments.

On a local scale, pollution monitoring can also benefit from new technical developments such as AUVs, Remotely Operated Vehicles (ROVs), and underwater acoustic communications systems. The technological requirements for pollution monitoring are similar (although not identical) to the requirements imposed by studying global climate change. The temporal scales of local pollution monitoring can be significantly shorter than for global effects. In particular, trying to understand the impact of episodic events on local environments (e.g. storms, oil spills, plankton blooms, etc.) requires a rapid response to the event and the synoptic characterization of the affected body of water.

Objectives

A two-day workshop was held in Brighton, UK, in March, 1994 to consider the application of new technologies (such as AUVs) to understanding the global climate and to monitoring of local pollution. The objectives of the workshop were:

1) To define a range of project topics, targeting strategic research needs and underpinning technologies; and

2) To create a framework of US/UK cooperation to implement those projects most effectively.

This workshop was sponsored by the Marine Technology Directorate, Ltd. (MTD) in the U.K. and the Ocean Engineering Program of the National Science Foundation (NSF) in the U.S. It was held on March 6 and 7, 1994, at the Hotel Metropole, in Brighton, England. A complete list of the delegates and their affiliations can be found in Appendix A.

Structure of the Workshop

The attendees were divided into four working groups, based on their areas of interest and expertise. The assignments of delegates to their working groups can be found in Appendix B. The groups were:

Group I:	Modeling and Simulation
Group II:	Sensing and Measurement
Group III:	Vehicles and Instrument Platforms
Group IV:	Control and Communications

During the course of the meeting, each group met in five sessions, and each session focused on a different aspect of the problem. After each session, the group leaders summarized the results of the session for all participants. The summaries were followed by general discussion to ensure that the working groups did not diverge. The sessions were:

Session 1:	Define Requirements, Identify Technology Needs
Session 2:	Summarize Ongoing Activities and Partnerships
Session 3:	Identify Priority Topics
Session 4:	Define Scope of Program
Session 5:	Develop Plan for Cooperation

After the fifth working group session, the entire assembly met and agreed on a set of conclusions and recommendations to be presented in this report. The chairs of the working groups agreed to produce summaries the findings of their groups for inclusion in the final report. The final report was produced by Dr. James Bales and Dr. James Bellingham of MIT, based upon the summaries provided by the working-group chairs.

MODELING AND SIMULATION

Co-Chairs: Richard A. Gould (U.S.) and Grant E. Hearn (U.K.)

It was evident from the start of the Workshop that the U.S. and U.K. contingents were initially pursuing different agendas and were at risk of working at cross purposes. The declared goal of the U.K group, as represented by MTD (the Marine Technology Directorate, Ltd.) was "Cooperation for Cleaner Seas," with a broadly based conservationist focus. The U.S. group placed greater emphasis on the specific goal of developing and applying autonomous underwater vehicle (AUV) technology to address conservationist needs. So it became apparent that the Workshop would provide a valuable opportunity to identify areas of common interest in relation to these different agendas with the aim of achieving commonalties of interest and generating productive joint U.S.-U.K. research.

The first session of Working Group 1 ranged over a series of predominantly scientific interests, with less emphasis on engineering applications. This was a useful session, not so much for proposing specific projects, but for building a consensus concerning approaches and procedures. We were asked to provide an "overall framework" to guide and structure discussions taking place within other working groups. This was facilitated by the willingness of the participants to examine critically key assumptions that apply to such efforts. Concepts such as the "random sea model," the need to distinguish between "prevention" and "mitigation" in environmental monitoring of the oceans, and relative scales of monitoring efforts were examined. As a first step toward the desired framework, Working Group I identified a series of linked, general operating procedures.

1. The ocean environment is modeled in order to simulate the behavior of marine devices operating in the context of controlled situations.

2. Successful modeling requires both understanding the processes involved and being able to measure their degree of interactions. Convincing results will be obtained by recognizing the appropriate temporal and spatial scales of the variables involved and by identifying technologies capable of generating reliable data over these spatial and temporal scales.

3. Obtaining reliable data includes examining the assumptions upon which the data collection is based.

4. Convincing assumptions in data collection enable the extension of results from one situation to another and from one level of scale to another.

Given these operating principles, what kinds of data can best explain the interactions taking place within the total marine environment? The following day's discussion addressed this question by focusing on specific common needs that combined the environmental monitoring concerns of the U.K. participants and the interests in AUV applications of many of the U.S. group.

On Day 2, we built on our earlier discussions and focused on potential commonalties in the area of monitoring ocean environments. The first major domain of common interest to be identified was Pollutant Sources, involving models of dispersal and transport in relation to the total environment and measurement of a wide variety of factors. Specific issues included:

a. *Wave action*, especially the interaction between surface waves and stratified layering below the surface. There is clearly a need to monitor and model mixing and movement within this critical zone.

b. *Source modeling*, involving outfalls and other sources and the spread of pollutants from these sources.

c. *Density field* monitoring, particularly to measure changes in concentrations of key indicators of pollution.

d. *Substrate effects*, focusing on processes by which: i) pollutants come to rest on the seabed and penetrate into the substrate; and ii) pollutants in the substrate can re-enter the water column.

e. *Chemical indicators*, specifically hydrocarbons, heavy metals, and nutrients, distributed within the oceanic environment. It was agreed that these indicators were especially diagnostic of critical problems in the environment and required special attention with regard to the use of monitoring technologies.

The second major domain of common interest to be identified was the need for reliable data. At first glance, this appears to be a truism. But our discussions revealed serious inadequacies at present in certain kinds of data on environmental processes that need to be remedied by improved monitoring technologies.

a. *Real-time interactive data.* Such studies have already been successfully accomplished on a trial basis and point the way toward environmental monitoring where data-collection strategies can be altered in real time in reaction to the data being acquired. Such approaches put special emphasis on effective and reliable underwater communications between underwater sensors and shore- or ship-based controllers.

b. *"Event-activated" monitoring.* Major gaps exist in our understanding of episodic processes, e.g., storms, die-off of marine organisms due to radical environmental perturbations, etc. Obtaining timely information when these events occur requires having unmanned sensors available, either stationary or on mobile platforms, that are activated by the perturbation and will collect data over the duration of the event.

c. *New sensor technologies and techniques,* This area is discussd in the next section.

d. *Vortex observation.* This relates back to our concern for better studies of wave action, including both breaking waves and internal waves.

e. *Data fusion presentation.* Technologies are needed that will ease the coordination of different data sets (often generated by different methods) to produce coherent, integrated results. For example, there is a need to improve the algorithms that coordinate surface and subsea positioning systems, especially when planning to use AUVs as data-collection platforms. In carrying out the data fusion, methods must be developed for dealing with the varying uncertainties in the different data sets.

f. *Existing "platforms of opportunity"* for environmental monitoring. These include both fixed platforms such as existing oil and gas rigs as well as mobile platforms such as ships. Some work is being done using commercial shipping, but their role could be expanded.

g. *Sampling strategies.* Uniform sampling in space and time is not necessarily the most efficient use of limited resources. Sampling strategies that can use current (and past) measurements to modify the search strategy in real-time promise to improve the efficiency adapt in real-time to the observed phenomena are needed to reach the full potential of new oceanographic technologies.

h. *Subsea navigation and positioning.* There is a clear need to define the parameters of positioning accuracy for different underwater monitoring applications. For example, sub-meter accuracy required for the management of submerged cultural resources at the seabed, while accuracies of order a kilometer are sufficient for studying large-scale ocean phenomena.

The third major domain of common interest was the need for improvement in modeling. Specifically, this refers to differences in modeling philosophies that can produce differences in data collection for complex ocean systems. Three examples were cited where it would be worthwhile to examine modeling philosophies and goals: 1. Combined vehicle and ocean dynamics, 2. Atmospheric transport models, and 3. Propulsion and energy system interactions.

The final session of this working group focused on preparing a series of joint U.S.-U.K. research projects that could be funded and carried out in the near future. These are summarized here in a ranked order of priority:

1. *Ground-truthing.* The need for ground-truthing is exemplified by the "SeaWifs" satellite observation program. Information on this program has been collected by Professor G. E. Hearne. The project involves deploying monitoring devices in areas to be covered by the satellite as it observes and records chlorophyll and other materials in

these areas. Since the satellite is scheduled for launch in late 1994, any response to this need should be timely. Shallow waters are likely to introduce erroneous readings due to reflectivity from the seabed and other factors. Therefore, it is especially important to test evidence about the presence of chlorophyll from satellite observations against simultaneous monitoring of chlorophyll in the shallower areas covered by the satellite survey.

2. *New sensors.* This area is addressed in the next section.

3. *Dispersal of pollutants*, especially in relation to wave action. It is especially important to be able to monitor dispersal and transport due to turbulence and mixing and to be able to model the different ways these processes operate at the pollutant source (e.g. the outfall, river mouth, etc.) as opposed to offshore and open ocean environments.

4. *Modeling complex systems.* Several examples of such modeling were presented during the working group's discussions, including a) prevention and/or mitigation of pollution from ship operation; b) harbor cleanup projects, where there is a need to apply different models to direct the monitoring of different factors affecting water quality; and c) post-depositional transformations of shipwrecks and other submerged cultural resources on the seabed due to measurable factors like corrosion, marine growth, silting, wave action, etc.

5. *Precise underwater positioning systems.* This was seen as a multidisciplinary effort to determine the parameters of accuracy required by different marine sciences--in particular, archaeology, geology, and marine biology--when taking measurements and deploying sensors. Such research will be needed to take cost-effective use of AUVs in different data-collection tasks, both in the water column and on the seabed.

6. *Explore use of existing "platforms of opportunity"* for ocean monitoring and data collection. At the present time such platforms are especially numerous in areas likely to be most affected by oil spills and other pollution, such as the North Sea and Gulf of Mexico. The utility of these platforms for ocean monitoring needs to be explored.

SENSING & MEASUREMENT

Co-Chairs: Roy Halliwell (U.K.) and James W. Bales (U.S.)

Introduction

All efforts to characterize the marine environment are contingent on possessing instruments capable of measuring its salient features to the requisite accuracy. We chose to catagorize these instruments as measuring physical, chemical, or biological parameters. For all three classes of measurements, in-situ measurements were recognized as enabling the widest range of new capabilities, particularly when combined with new instrument platforms and communications technologies. However, we recognize that the recovery of physical samples for later analysis (on shipboard or ashore) will continue to be part of regular operations for the foreseeable future. The scope of our discussions was limited to measurements made within the water column or benthos.

We began by listing, as best we could, all parameters of interest in sensing, understanding, and (if necessary) remediating local pollution and global climate change. Separate lists were generated for physical, chemical, and biological measurements. The following constraints were considered necessary conditions for further consideration of a measurement:

Feasible

Not commercially available

Widely applicable

Of interest to parties in both the U.K. and U.S.

Some potential market exists

Existing laboratory-based systems that can be made to operate in-situ (with some research and development effort) were included. Parameters (such as CO_2) where major efforts to develop in-situ sensors are already being pursued were excluded, to avoid duplication of effort.

Further selection was made by applying a second set of criteria identifying desirable traits in a measurement system.

1) In-Situ

2) Real Time

3) Low Cost

4) Small Size and Weight

5) Low Power Consumption

6) Analytical Reliability

7) Data Quality/Verifiability

8) Endurance

9) Physical Robustness

10) Interoperability

The first two attributes are driven by a desire to obtain data in a timely fashion. With an in-situ, real-time system, researchers in the field can modify their data-collection strategies to best use the limited resources found in field operations. By low cost, the third attribute, we envision a measurement system whose total cost would be low enough to permit widespread use by virtually every company or local authority with the need for such data. The next two attributes are desirable to allow operation from the new instrument platforms under development (discussed by Group 3), as well as to take full advantage of the recent advances in undersea communication technologies (discussed by Group 4). Attributes six through nine are fundamental to any oceanographic instrumentation and are almost always open to improvement for any given system. The importance of the final attribute, interoperability, has been well described by Group 3.

The panel went down the initial list of parameters to be sensed. For each item the criteria above were used to identify those areas where joint U.S./U.K. research efforts are most likely to enhance our abilities to detect, monitor, and remediate pollution in marine environments. The systems identified as the most promising are:

Physical: Mid-Water Particles
Sea-Bed Characterization (Benthic Granularity)
Turbulence

Chemical:	Nutrients Metals Hydrocarbons
Biological:	Productivity Benthic Sampling In-Situ Benthic Population Assessment

Finally, we noted that a universal concern for all in-situ systems is biofouling. We feel that antifouling strategies are a fourth area where there is the potential for a US/UK collaboration. Each of these four items item are discussed in turn in the next section.

Potential Areas for U.K./U.S. Collaboration

Physical - The driving force in sensors in the oceanographic environment is to move the measurement in-situ, providing a measurement of an undisturbed sample in the context of its environment. One technology driving the move to in-situ sensors are the continuing reductions in the size, power consumption, and cost of embedded computers. This is leading to a new generation of "smart" sensors, as well as enabling sensors which gather data by sampling and then carrying the sample through a controlled process.

Improved knowledge of midwater particles will aid our understanding of pollutant fluxes between the water column and suspended particles, as well as between particles and the substrate. The parameters to be measured would include the size and composition of particles in the water column. A combination of optical sensors, structured light fields, image processing, and water flow sensors shows promise as one method for making these measurements in-situ, in real time.

There is a need to characterize the seabed, in particular, to determine the granularity (or distribution of particle sizes) of the bottom sediment. Knowledge of granularity is needed to understand the transport of pollutants between the water column and the seabed. Here a measurement system might include mechanical sampling, sample processing, and mass or optical size measurements.

Measurements small-scale turbulence and shear in the water column are needed to quantify and predict the transport and dilution processes affecting pollutants. Here the creation of small, low-power, low-cost sensor systems for use on platforms such as autonomous underwater vehicles could have a significant pay-off.

Finally, we note that the defense industry has developed a wide range of sensing technologies. The recent interest in defense industry conversions may provide an opportunity to develop these technologies for use in pollution monitoring and remediation. Two promising examples of such technologies are optical sensors and remote imaging techniques.

Chemical - The Sensors and Measurement Working Group identified a wide range of chemical variables that must be known to evaluate the effects of human activities on the marine environment. These include the major biological nutrients (phosphorous, nitrogen, and silicon), chlorophyll, carbon dioxide, oxygen, pH, potentially toxic metals (Cu, Cr, Zn, Cd, Hg, Al), hydrocarbons, pesticides, PCBs, PAHs, and radionuclides. As discussed above, we reduced the scope to those variables in which we can identify both U.S. and U.K. interest, can feasibly be brought In Situ, and have a potential commercial market. Finally we excluded from our focus those variables that are already receiving considerable attention such as carbon dioxide, oxygen, and chlorophyll.

We believe that nutrients, metals, and hydrocarbons are three variables that are amenable to in situ measurement with moderate research and development. Several approaches can be considered, including miniaturized chemical analyzers based on flow-injection analysis, gas chromatography, and electrochemical solid-state sensors. The specific types of considerations that are appropriate for joint U.K. - U.S. cooperation include the development of specific prototype systems, addressing the need for in situ calibration, and the evaluation and adaptation of non-marine analytical technologies (e.g. medical or automobile combustion monitoring) for use in marine applications.

Biological - There is an urgent need for a core sampler capable of taking an undisturbed core of approximately 5 cm diameter, to a depth of 10 cm. Although there are instruments in existence capable of taking such samples, they are limited to a narrow weather window, needing calm weather to operate, and will only operate satisfactorily in muddy sediments. Routine monitoring, as is required for pollution impact studies, requires an instrument capable of 1) sampling a wide range of sediment grades and 2) operating in a wide range of weather conditions. Finally, the instrument should be capable of collecting multiple samples without returning to the surface between sampling cycles.

Productivity is one measure of the "health" of the environment. The introduction of waste material into a system can be both enhance or reduce productivity, depending upon the contaminant and the conditions. There is a requirement for instruments capable of measuring productivity in the water column and/or the seabed. The principles of such measurements are well established, but there is a need for miniaturization of the technology for real time, in-situ measurements.

Analysis of benthic communities currently involves destructive sampling and lengthy processing in the laboratory. This methodology precludes the rapid response to an episodic event as well as limiting our ability to extensively survey benthic communities. There is a need for in-situ monitoring of the structure of benthic communities, preferably in a non-destructive fashion. There has been some work in applying optical and acoustic techniques to make this measurement. Much work remains before a mature technology is in hand to meet this need.

Antifouling Strategies - Whenever oceanographic measurements require long-term deployment of sensors, even the most routine measurements can be severely affected by biofouling. In most cases it has not yet proven possible to protect the active parts of sensors against microfouling (the formation of biofilms of bacteria, algae, etc.). Such films have significant effects on, for example, membranes and optical surfaces, reducing data quality over short time scales. This leads to a requirement for frequent and expensive maintenance to maintain sensor integrity. In addition to these problems there is a requirement to move towards more environmentally acceptable methods of antifouling treatment of the bodies of sensors and platforms.

The success of prolonged oceanographic measurement campaigns, using both existing sensor technology and new types of sensors, is strongly influenced by the ability to provide resistance to microfouling to maintain data quality. There is an urgent need to develop antifouling strategies for the protection of sensor elements, in such a way that the antifouling treatment does not itself perturb the measurement.

Mechanisms for Cooperation

The panel felt that mechanisms must be established to support joint U.K./U.S. research in the areas identified above. Our discussion led us to propose one possible mechanism for selecting and funding such collaborations. In addition, several other suggestions to foster and support such collaborations were put forward.

We propose a follow-on meeting, with the explicit goal of producing specific, joint research proposals that will be submitted to funding agencies in both countries. The following procedure was recommended for selecting the attendees at the follow-on meeting.

> The MTD and NSF each issue a call for pre-proposals. The call would include this report.
>
> Individual researchers would have six months to contact potential collaborators across the Atlantic and submit a pre-proposal describing the research they wish to conduct and how that work fits into the needs identified at this workshop. The pre-proposals must include investigators in the U.S. and the U.K.
>
> Pre-proposals would be winnowed by a bi-lateral committee supported by MTD and NSF.
>
> Researchers whose pre-proposals were selected would attend the follow-on meeting to develop full proposals for submission to the funding agencies.

Other suggestions for enhancing collaboration between the U.S. and the U.K. were also put forward. These suggestions could occur with the framework of the procedure described above, or could be implemented independently. They include:

> Personnel Exchange: Three month to one year exchange of personnel at the Ph.D. level (for academics) or Engineer/Scientist level (for industrial participants).
>
> Enhanced Travel Funds: Joint efforts require PIs to spend significant lengths of time with their collaborators working directly on the research effort.
>
> Data Exchange: "Collaboration by Internet" is now feasible. Mechanisms for data exchange will enhance this ability.
>
> On-Line Consulting: Where problems common to groups in the U.K. and U.S. have been identified (e.g. oil-spill response), the existence of the Internet opens a new avenue for interaction between researchers.

VEHICLES AND INSTRUMENT PLATFORMS

Co-Chairs: Stephanie Merry (U.K.) and Samuel Smith (U.S.)

Requirements

The group identified three problem areas where significant advances could be made through the development of vehicles and instrument platforms.

I. Temporal and spatial under sampling of pollution levels

There is a need for more efficient monitoring techniques (i.e. more data, on a shorter time scale), in order to develop accurate pollution models. More robust, low cost sensor packages are also required, even if it is necessary to sacrifice high level accuracy. It was noted that Liverpool and Boston have similar pollution monitoring requirements. Measurement and sensing requirements include:

Metals and radio nuclides	Dissolved organics
Ammonium nitrate and sulfide	Plankton
CO_2	Hydrocarbons
pH	Chemicals
Turbidity	Bacteria and pathogens
Nutrients	CTD

2. <u>Pipeline Survey</u>

There is a legal requirements for annual pipeline surveys in the UK and in the USA, although the interpretation of this requirement is often lenient. Nonetheless, the oil industries make significant expenditures each year to inspect submerged pipelines. This is an area where new technologies might lower costs and improve the environmental protection provided by inspection.

3. <u>Sub-bottom characterization</u>

There are several applications where some degree of sub-bottom characterization is required. Both industry and public agencies need this capability to locate certain sources of pollution, inspect buried pipelines and effluent tunnels, and monitor dredge spoils. Particular reference was made to submerged cultural resources, such as submerged prehistoric terrestrial sites and shipwrecks.

On-going Activities and Priority Topics for Further Research

Although many types of instrument platforms were identified, delegates centered on AUVs and ROVs for deep water operation. This was felt to be an area where significant technological advances will provide significant payoff, and which might therefore attract funding for cooperative research.

Information on national research activities may be found in several publications. In the UK, sources include

MTD Directory of Current Projects
MAST Directory and EUROMAR Market
ROV Review
Proceedings of Oceanology
North Sea Oil and Gas Directory

In the US, sources include

Sea Technology Magazine and the Sea Technology Buyers' Guide
Underwater News and Technology Magazine
"Scientific and Environmental Data Collection with Autonomous Underwater Vehicles", Workshop in Cambridge, MA, MIT Sea Grant Report 92-2, 1992.
Proceedings of ROV; Oceans; and the IEEE Symposium on AUV Technology

A lively discussion ensued on the subject of areas which require development in subsea vehicles. The themes of miniaturization and cost-effectiveness cropped up regularly. The following list of desirable enabling technologies was generated. They are listed by their relative priority, as determined during Session 3:

1.	Communications	RF; satellite; acoustic; optical
2.	Propulsion Systems	Power sources; motors and thrusters; hydrodynamics
3.	Cost-effective operation	Cost versus reliability and robustness; interoperability and modularity; miniaturization; low power demand
4.	Command center and mission	Control strategies; obstacle avoidance
5.	Navigation and ranging	Vision; optical/acoustic scanning ranging
6.	Sampling device and manipulators	

In order to determine the parameters for the above research topics, the group decided it would be beneficial to define one or two mission specifications for an underwater vehicle. The vehicle was to be untethered, but acoustic communications might be desirable.

The missions were chosen to match two of the requirements identified during the first session: Pipeline Survey and the Under-Sampling Problem. For the latter, a mission of monitoring coastal water pollution was selected, to using the expertise of delegates from Boston, USA and Liverpool, UK (both coastal cities with major coastal pollution problems). The idea of "twinning" geographical locations in the US and UK with similar pollution problems was discussed; it would be interesting to find a UK site to twin with the Indian River in Florida, where agricultural run-off is the major concern.

Program scoping

Dr. Mickelson (Massachusetts Water Resources Authority) defined the requirements for a mobile/ambulatory sensor platform for pollution monitoring. His description is presented in Appendix C. Mr. Winchester (MTD) and Mr. Clark (Harbor Branch Oceanographic Institution) carried out a similar analysis for pipeline monitoring, which can be found in Appendix D.

For pollution monitoring, the advantages of a mobile platform over a fixed platform include:

- one sensor package (costing approximately £25k or $37.5k) operates over multiple locations
- the cost of moorings (approximately £133k or$200k) is removed
- vandalism of fixed platforms is avoided
- fixed platforms constitute a navigational hazard
- succession data of long term temporal changes (e.g. video of bottom features) is more cost-effective if an ambulatory platform is used
- short term monitoring (e.g. during weather events) is more cost-effective from a mobile platform.

The AUV performance specifications for these two missions were then defined as follows:

Table 1: Performance Specifications for AUV Missions

Performance Parameter	AUV Mission	
	Near Shore Data Collection	Pipeline Survey
Operating Depth	200 m	400m
Altitude/Depth Hold	± 0.25 m	± 0.05 m
Horizontal Positioning	± 10 m	± 1 m
Speed	3 kt	6-7 kt
Endurance	12 hours (one tidal cycle)	12 - 24 hours
Obstacle Avoidance	Yes	Less Critical
On-Board Data Storage	Yes	Yes
Data Transmission	Maybe	Yes: on-line

From these case-studies, we established the priorities of the six enabling technologies as:

1. Cost-effective operation
2. Navigation and ranging
3. Command center and mission
4. Communications
5. Propulsion
6. Sampling devices and manipulators

Cooperative Plan

The Working Group agreed that the cooperative plan for research should include the development of demonstrator test vehicles, as proof of concept for the use of AUVs in both the pipeline survey and coastal pollution monitoring tasks. For the pollution monitoring task, two capabilities are of interest over the long term; multiple-vehicles measuring water-column parameters in a cooperative fashion, and a site-revisitation capability.

To address the specific research topic of cost-effective operation (which was afforded highest priority), it was proposed to develop a research program addressing "Distributed Control Structures and Protocols for Interoperability." Interoperability is most simply defined as "Interchangeable Parts", and more broadly includes standardization of design features such as communications protocols, power bus specification and physical form factors. Cost-effective operation is of particular concern for the pipeline following application, where there is an existing technology for carrying out that mission, albeit a relatively expensive technology. The next priority, navigation, is of particular importance for the pollution monitoring mission, as these missions often take place in shallow waters where reverberation, multi-path, and attenuation degrade traditional acoustic navigation methods.

CONTROL AND COMMUNICATION

Co-Chairs: Daniel Spagni (U.K.) and Josko Catipovic (U.S.)

The overall objective of the workshop was to identify the advances in science and technology required to improve our abilities to characterize and remediate marine environments. Work Group IV was tasked with defining requirements and establishing priority topics in the field of control and communications.

The results of this working group's discussions are summarized below.

Control Technologies

It is possible to divide the control requirements discussed into three broad areas; control technologies for fixed sensor arrays, control technologies for towed arrays and control technologies for unmanned underwater vehicles.

The technologies that are currently mature and readily available enable: the sophisticated operation of fixed sensor arrays subsea; a degree of control over the altitude at which arrays can be towed; and limited operation of unmanned underwater vehicles in open seas.

The Working Group identified the following control technologies as enabling technologies for monitoring subsea pollution:

1. Adaptive management of sensor systems
2. Component (software and hardware) design for inter-operability and reuse,
3. Control Systems for deployment/docking/recovery/replenishment
4. Trajectory control (including control of the vehicle orientation)
5. Effect of the level of quality of the sensory feedback on the trajectory control
6. Localization/Guidance/Navigation
7. Obstacle avoidance

The first three technologies are relevant to fixed and towed arrays as well as AUVs. The next three technologies are common to the control of towed arrays and unmanned underwater vehicles. Implicit to the last technology is the issue of the legal liability of the operators of AUVs and ROVs. This is a particular concern in enclosed areas (such as ports, harbors, bays) where ships movements, and man-made objects (e.g. lobster pots) are likely to be frequent. Each of these areas is discussed in turn below.

1. Adaptive management of sensor systems: Adjusting the mode of sensor operation in accordance with the prevailing circumstances provides two advantages over continuos data logging. First, significant power savings can be obtained. Second, the amount of raw data collected can be reduced without throwing out information. An obvious example of this is controlling the rate at which readings are taken in response to changes in the parameters being measured. Such adaptive systems are now mature in the laboratory, and there is wide experience on both sides of the Atlantic These technologies could be readily applied to the control of fixed and towed array sensing systems, both for the adaptive control of the sensing mode and the interpretation of the sensor readings.

2. Component (hardware and software) design for interoperability and reuse is essential for the commercial viability of the technological innovations discussed by the sensing and platforms working groups. Interoperability will improve the flexibility of new systems, which should result in less downtime and reduced mission/operating costs. As yet, little attention has been paid to this area, since the technologies involved have all been developed in the research community. As technologies are transferred into the commercial sector, the importance of interoperability will increase.

3. Control systems for deployment/docking/recovery/replenishment are fundamental to undersea operations. Fixed arrays are deployed into "known" regions, although placing the area in a precise location may not be critical. A more serious issue is that of powering the system and replenishing that power, especially in deep sea deployment when the use of an umbilical is often impractical. Options include servicing by AUVs or ROVs, or simply dropping replenishment power supplies onto the system from a surface vessel. Finally, fixed systems can either be retrieved at the end of their operating life, or (if their data has been recovered) left on the seabed. Retrieval is often desirable for data-recovery, as well as for pollution reasons.

4. Trajectory control (including control of the vehicle orientation) is important on tow-fish and towed arrays, remotely operated vehicles, and autonomous underwater vehicles. In the case of the towed array, cross currents tend to displace the array from the path of the towing vessel. Correction is therefore required to correlate the measurements from the array with actual path followed by the array. For many systems (e.g. side-scan sonars) the orientation of the array is also important. The decision on whether to control the orientation or simply record the orientation and correct the data in post-processing must be made on a case-by-case basis. Similarly, arrays used to measure vertical gradients in the ocean currents will therefore require some form of altitude/depth control. The same comments are also true for AUVs and ROVs, and are related to the issue of navigation.

The control of towed arrays and ROVs can utilize state of the art technologies to achieve its objectives since a number of reference signals can be set up between the mother ship and the array via the tether. The sensing problem then simply becomes one of keeping the reference beams in alignment and measuring relative changes in the beam directions. The problem for the control of AUVs is to sense small relative changes reliably. Controlling the orientation of the vehicle can be simplified to some extent by the proper hydrodynamic design of the skin of the array or the vehicle.

5. The quality of the sensory feedback can dominate the accuracy of the trajectory control, as discussed above. Often the uncertainty caused by the inherently noisy sensor environment subsea prevails. This issue is acute for AUVs. Techniques are needed to determine trends from noisy, slow moving data (such as the output of a magnetic compass). One area where work is needed is to determine the relative robustness of the various control techniques available to this noise.

6. Localization/guidance/navigation is one of the fundamental problems for making measurements in the ocean. There are a limited range of reliable techniques for accomplishing this task. Many of them require either deploying acoustic aids in the area of interest before operations begin, or tracking a platform from a dedicated surface vessel.

One option in open seas uses a combination of the use of Global Positioning Systems (GPS) and Inertial Navigation Systems (INS). In this scenario, the vehicle returns to the surface periodically to obtain a navigation fix via GPS (or, the vehicle could approach a buoy that carries a GPS receiver and be given a fix via acoustic modem). In between these fixes, the vehicle uses its own onboard inertial system to estimate its position. Accurate Inertial Navigation is difficult underwater because of the low vehicle velocity and the unpredictable nature of the prevailing currents. The problem is most acute for a slow-moving vehicle in slowly-changing currents, since the rate change in the two velocities (vehicle and water)is quite small and difficult to detect. Acoustic velocity logs (Doppler or Correlation systems), used in conjunction with angular rate sensors and a heading reference, may prove to be a viable alternative.

Closer to shore, a variety of techniques are used. Acoustic beacons can be deployed (at some expense) in the area of operation. In shallow water, acoustic navigation systems are degraded by reverberation, energy loss into the bottom, and multi-path. Additional research is needed to develop robust acoustic navigation in shallow water. Periodically surfacing to obtain a GPS position is more attractive in shallow water as the energy cost of surfacing and diving again is less than in deep water. Another option, for areas that are well surveyed and/or will be the scene of repeated operations, is to develop map-matching algorithms analogous to those used by cruise missiles.

7. Obstacle avoidance is critical for operations in shallow water or in rugged, unknown bathymetry. In harbors and near shore an important issue is avoiding man-made structures and systems (e.g. lobster-pots, moorings, boats, piers, etc.) where a collision raises concerns of legal liability. In all areas where autonomous or semi-autonomous systems may operate, the general problem of detecting and avoiding obstacles in unknown areas is not yet solved.

Communications

The Working Group decided to concentrate its attention on underwater acoustic communication, rather than on electrically wired systems because of the versatility and flexibility of acoustic systems. Optical systems for short-range communication are undergoing rapid evolution at this time and may be considered for future efforts.

The Group identified the following scientific and technological requirements for the establishment of operational acoustic communication systems:

- Multiple moving sensors with 2 way communication at a rate of 10 kilobits per second per link, with real time data recovery and control.
- Rapid deployment (set up in half-day) and recovery.
- Adaptive communication over ranges of 60 km (position, congestion, through-put limits, dynamic routing).
- Robustness to interference, both channel characteristics (thermal gradients, turbulence, multi-path), and man made noise (sonar, other users).
- Reliability, both long term reliability in general and reliability for safety critical applications.
- RF communication interface between equipment in the field and a shore station.

- Accurate site revisitation (for photomosaics and for long-term study of specific micro-habitats and small-scale phenomena).

These capabilities could be obtained by a network of stations emplaced around the area of interest. Each station would include an acoustic navigation beacon, and (optionally), an acoustic modem as well as some set of sensors. Mobile platforms, moving within the network, would concentrating measurements in areas with high temporal or spatial variability. Researchers (or local authorities) on shore would have continuous access to the data through an RF link to one (or more) of the stations. Through this link, the scientists could redirect the mobile assets (or reconfigure the operation of the stations) to optimize their data collection in real time.

To achieve these benefits requires creating certain new technologies. They are:

- Accurate acoustic navigation in shallow water environments
- Robust acoustic communication in shallow water environments
- In-situ sensors
- Theory of advanced sampling strategies
- Coordination of multiple vehicles
- Dynamic Control of an AUV in an energetic event
- Reliable AUVs

It is clear from the workshop that the interest exists for a joint US/UK research program to address these issues. The next step is to outline how such a program might be organized.

Outline of Program

The first issue to be addressed is accurate acoustic navigation in shallow water environments. This requires two efforts. The first is to develop advanced methods for modeling the dynamic acoustical properties of shallow water environments. The second is to develop "smart beacons" capable of using the model to adapt their operating parameters for optimum performance. Work in the Arctic has shown that such models can be used to obtain a measure of the properties of the water column. In fact, the beacons can use the acoustic model to carry out acoustic tomography. The beacons, except for one, would be bottom moored in a test area, with the final beacon attached to a platform (fixed or mobile) piercing the surface to make radio contact to a shore station.

With the navigation network is in place, vehicle operations would begin. Initial tests should evaluate the performance of the navigation system and demonstrate its capabilities. The next step would be to add mission sensors (e.g. CTD, fluorometery, turbidity) to the vehicle, with data collected under the supervision of an interested scientist or local authority. The workshop participants noted that Boston Harbor and Liverpool Bay might represent a suitable pair of sites. Once network demonstrations are completed in the initial locations, it is important that a second set of trials take place in a different acoustic environment. The mission payload could be modified to meet the interests of researchers working in that area.

The acoustic model developed for navigation purposes could also be used to enhance acoustic communication. When this stage has been reached, an acoustic communication network should be integrated into the mooring/vehicle system.

The need for interoperability was stressed repeatedly by the participants at the workshop. Therefore, a parallel effort should be undertaken to advance the state-of-the-art in distributed control-architectures for AUVs. Currently, there is limited commonality between different AUV programs in the areas of intra-vehicle communications protocols and distributed architectures. The creation and implementation of a robust, high-speed local-operating-network for AUVs would greatly enhance vehicle reliability. Such an architecture would rapidly become a de facto standard, leading to greater interoperability between subsystems developed by researchers on both sides of the Atlantic.

Parallel efforts should be undertaken to advance the state-of-the-art in sensor and measurement technologies and develop communication and ranging techniques for multiple vehicle operations. For the first parallel effort the goal should be to develop new in situ measurement capabilities, with an emphasis on compact, low-power systems. For example, there are systems under development that show great promise for measuring various trace metals, a class that includes many major pollutants. The second parallel effort, communication and navigation for multiple vehicle operations, might consider novel new technologies. For multiple vehicle operations, control strategies based on nearest-neighbor interactions may prove to be the most robust. Here, the inherently short-ranged nature of optical systems may prove advantageous. For both parallel efforts, some effort should be made from the beginning of the program to ensure that the new systems are ready for integration into the vehicles as these new components come on line.

Once AUVs have begun to operate within these navigation/communication arrays in different locations and under a wide range of conditions, research should turn to identifying the issues for the next generation of technology. This would probably include the last two capabilities listed above, control of AUVs during energetic events as well as lowering the cost and increasing the reliability of AUVs.

ANGLO-US MEETING ON COOPERATION FOR CLEANER SEAS
BRIGHTON, UNITED KINGDOM
6-7 MARCH 1994

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APPENDIX C – MULTIPLE PLATFORMS SURVEYS OF BOSTON HARBOR AND LIVERPOOL BAY

Dr. Mike Mickelson, Massachusetts Water Resources Authority

Informed management of impacted coastal waters such as those near the cities of Boston and Liverpool requires information at appropriate spatial and temporal scales. Conventional ship-based surveys are often lacking in this regard: an expert review panel of Boston's monitoring program highlighted the need for filling in temporal gaps and for providing a synoptic 3-D view of the complicated mixing patterns. Addressing these data needs will require introducing a higher level of technology into the monitoring effort.

The technologies of sensors, platforms, and communications are now mature enough to warrant a demonstration of their value in surveying the extent of coastal pollution from metropolitan areas. The demonstration would link technology and application by bringing together technologists who have these new tools and managers in need of cost-effective ways to document environmental problems and the improvements that may result from control measures.

Both cities have been discharging large amounts of waste into coastal waters for centuries, with deleterious effects on environmental quality including phytoplankton blooms, degraded bottom communities, and contaminated and diseased fish. Both cities, however, are now dedicated to improved control, treatment, and disposal. The spatial scales in Boston and Liverpool are similar, and traveling away from the harbor, salinity increases while turbidity, nutrients, and metal and organic contamination decrease. While the main environmental concern is nutrients in Boston, it is metals in Liverpool, reflecting the different loadings and assimilative capacities of two systems. Boston is planning to relocate the main source of contamination from the shoreline to a point 15 km offshore. Liverpool is trying to solve the more difficult problem of dealing with a large number of smaller sources. Planning for future improvements requires an understanding of the transport and fate of the contaminants which are now discharged into the receiving waters.

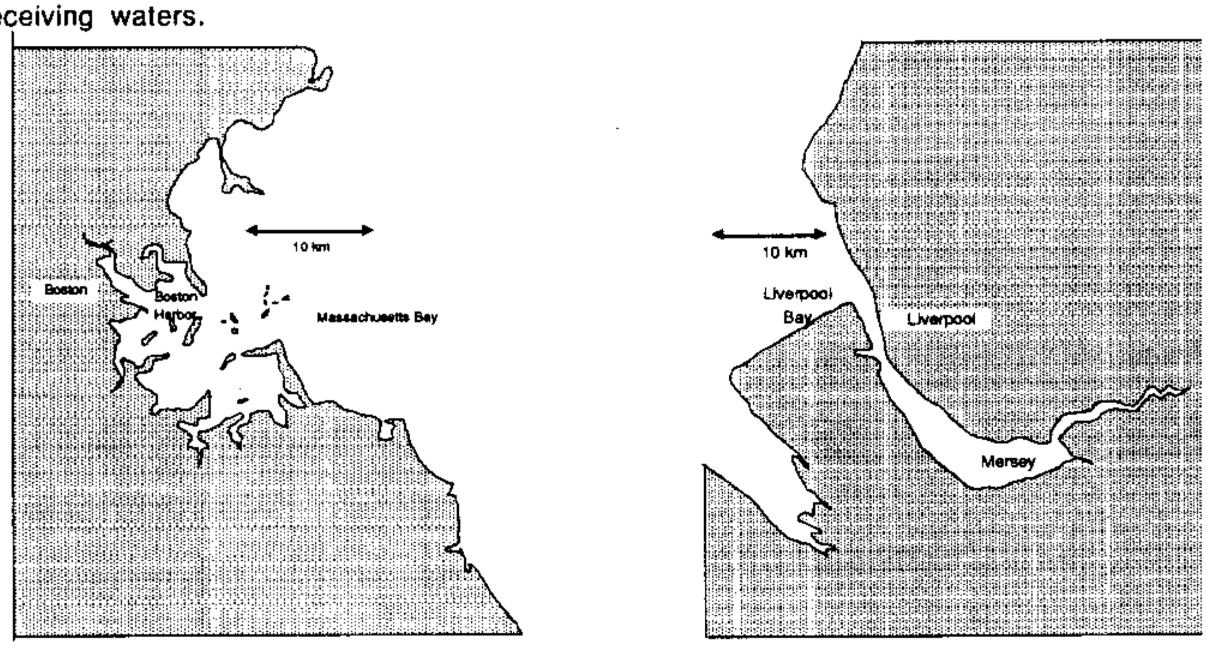

Figure 1: Left, Boston Harbor. Right, Liverpool Bay.

Members of the scientific, regulatory and environmental management community in Boston and Liverpool have expressed interest in the possibility of a cooperative demonstration project conducted in the two cities. In Boston, the demonstration would key into a range of ongoing programs, act as a catalyst for coordinating those efforts into an intensive experiment, and provide a base of experience for a follow-on experiment in Liverpool.

The survey could consist of both existing programs and demonstration programs.

Existing programs	Demonstration program:
Contaminants in sediments and sediment traps	Data collection with an AUV
Aircraft overflight of laser-induced fluorescence	Multiple AUVs for synoptic studies over large spatial scales
Shipboard water quality measurements	AUVs interacting with a network of modem-equipped moorings
Moored instrument platform	Moored instrument platforms with acoustic modems
Satellite remote sensing	

APPENDIX D – AUVS FOR PIPELINE INSPECTION TRIALS

Mr. Dick Winchester, Marine Technology Directorate

Dr. Andy Clark, Harbor Branch Oceanographic Institution

AUVs for pipeline inspection and seabed survey work have been under consideration for many years. It is a fact that industry is very skeptical about AUV capabilities and therefore, for these first trials it may well be sensible to choose the simplest of all the pipeline inspection missions - using a side-scan sonar with the principle goal of locating freespans. Typical lengths of pipeline (ranges) will be 5 - 20 km, in waters 50 - 100 meters deep.

Even for this relatively simple mission it is essential to use a surface support vessel fitted with a differential GPS naval system and an Ultra-Short Baseline (USBL) acoustic tracking system in order to track the vehicle and fix its absolute position. Thus, a degree of quality control can be applied to the navigation from the surface to check that the vehicle Doppler is behaving itself and also to correlate the pipe anode positions which can be picked out of the side-scan sidelobes. The type of surface vessel used can be much less sophisticated than that used with an ROV or even a towed fish system. It would therefore be much less expensive – one of the main arguments for trying to use AUVs in the first place.

The following instrument kit is envisioned:

a) Side-scan sonar - single or dual channel (typically a 200Khz system but a higher frequency would improve resolution). The second sonar channel is invaluable in the event the AUV crosses over the pipeline.

b) USBL transponder for tracking the vehicle.

c) Acoustic Data Link to record side-scan data and provide a control link. For commercial applications, it may be more cost-effective to record the data on-board for later recovery and post-processing. An acoustic data link may still be desirable for insuring quality control of the data in the field.

d) 3-Axis Doppler sonar

e) North Seeking gyro

f) Internal DAT recorder

Currently, annual inspections mainly use side-scan, although some video inspection work is still performed. Side-scan can reveal more than one might imagine. For example, a new anchor scour running over the pipeline may indicate the possibility of new damage, justifying a detailed inspection by ROV. Side-scan will remain the main tool for some time to come, particularly as improvements in both hardware and signal processing continue to be made.

One recent example of signal processing improvements is a very effective DSP kit (developed in the UK) which, in real time and on line, automatically identifies and measures the length of pipe freespans. Thus, one of the essential pieces of technology needed for AUV work is already in place. This side-scan DSP system can output a signal giving altitude and distance to the pipe – information which should preferably be used to guide the AUV, keeping it within the altitude and offset limits needed to maintain the correct angle to the pipe. An acoustic data link might be used to acquire side-scan data on the surface.

The trial would be performed over no more than a 20 km stretch of pipeline - the objective being to demonstrate the technology rather than to conduct an endurance test. A speed of four to six knots is reasonable for side-scan operation. Before launching the AUV for the at-sea demonstration a more conventional survey of the pipeline should be conducted with a towed system. Thus, be fore trials begin, the investigators will be armed with 1) a coordinate (GPS) map of the pipeline, 2) a continuous side-scan record of the pipeline for later comparison, and 3) a priori knowledge of potential anomalies, such as buried segments, free spans, and abrupt turns. If such a survey is not carried out before the AUV demonstration, then a pipeline that is already well documented should be chosen to provide a baseline for comparison.

There is a potential problem related to buried pipe: If the side-scan loses the pipe the vehicle loses its position reference. One solution is to instigate a "signal lost - switch to heading hold" routine, allowing the AUV to continue on the same heading until the pipe is picked up again. This explicitly assumes that the buried stretch of pipe is straight, a reasonable assumption since most buried sections are not too long.

Corrosion data acquisition requires a different type of survey, with the vehicle running close to the pie (1 m or less). This presents a different set of problems. The AUV would need a high-resolution, multi beam profiling sonar or pipe-tracking device to obtain altitude and offset references. The vehicle would also need a look-ahead sonar of the same type, and magnetometer (or other device) to detect the anode positions. In this mode, USBL is an essential element of the navigation system, as the curvature of a pipeline (and materials forming it) may degrade the performance of a Doppler system. In any event, corrosion surveys are less common than before now that a large body of historical data has become available. Corrosion surveys are more likely to be carried out by an ROV after pipeline installation and every few years thereafter.